Wide-bandgap semiconductor materials: For their full bloom†

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Wide-bandgap semiconductors are expected to be applied to solid-state lighting and power devices, supporting a future energy-saving society. While GaN-based white LEDs have rapidly become widespread in the lighting industry, SiC- and GaN-based power devices have not yet achieved their popular use, like GaN-based white LEDs for lighting, despite having reached the practical phase. What are the issues to be addressed for such power devices? In addition, other wide-bandgap semiconductors such as diamond and oxides are attracting focusing interest due to their promising functions especially for power-device applications. There, however, should be many unknown phenomena and problems in their defect, surface, and interface properties, which must be addressed to fully exploit their functions. In this review, issues of wide-bandgap semiconductors to be addressed in their basic properties are examined toward their "full bloom".

1. Introduction

1.1 From the dawn of compound semiconductors to wide-bandgap semiconductors

Since the realization of GaAs bulk single-crystal substrates in 1954, researchers of compound semiconductors have strived toward research on new compound semiconductors, alloy semiconductors, heterostructures, and device applications by referring to the chart illustrating the relationship between the bandgap and lattice constant of zinc blende structures.[1] Since the late 1980s, an increasing number of researchers have focused on the potential of semiconductors with a wider bandgap as next-generation materials, expanding the range of research on semiconductors to include those with hexagonal and orthorhombic structures. Figure 1 shows the relationship between the energy bandgap and bond length for various compound semiconductors that are promising for practical application. Table I summarizes the basic physical properties of various wide-bandgap semiconductor single crystals, which are now attracting many researchers.

An increase in the bandgap leads to short-wavelength emission and an increased breakdown electric field. These have opened new application fields of wide-bandgap semiconductors to LEDs and laser diodes (LDs) from the visible and short (blue-green, blue, and UV) spectra range and to power devices supported by high breakdown field.[9]

1.2 Brief history and current status of development of wide-bandgap semiconductors

In the late 1980s, group II–VI compounds, such as ZnSe, were intensively focused on as wide-bandgap semiconductors. This was because alloy-crystal systems with such as (Zn, Mg, Cd) and (Se, S), are lattice-matched to GaAs substrates, enabling the formation of heterojunctions that cover the blue-green to blue range, as shown in Fig. 1. Moreover, ZnSe substrates were developed and improved at this time. Although the development of ZnSe-based LDs with a wavelength of ~500 nm was reported by many researchers,[10-13] further progress was little because of their short lifetime. Especially after the emergence of high-brightness GaN-based blue LEDs in 1993,[14] the research on II-VI compounds had to be shrunk. However, many researchers who had “polished” their skills through research on group II–VI compounds shifted the target of their research to GaN-based optical devices, which greatly contributed to the subsequent progress of these devices. In addition, challenging research to address the issue of the short lifetime and develop green-to-yellow optical devices is still underway.[15]

On the other hand, in the 1980s and 1990s, marked progress had been seen for GaN toward practical blue LEDs with the evolution of extremely high-quality GaN epilayers on sapphire with low-temperature-grown AlN buffer layers,[16) p-type GaN by low-energy electron beam irradiation (LEEBI)[17) or thermal annealing,[18) and high-quality InGaN layers.[19) The series of evolution was bloomed as high-brightness blue LEDs using InGaN/GaN heterostructure in 1993.[14) Rapid progress in crystal quality of GaN[20) was promptly followed by high-brightness green LEDs,[21) blue/UV LDs,[22-25) and white LEDs,[25–27) leading to the practical application of solid-state lighting[28) and high-density optical disks. GaN alloyed with AlN or InN has been making progress as a material that covers the visible to deep-UV range.

SiC has mainly been developed as a candidate for power devices. The invention of step-controlled epitaxy[29,30) was promptly followed by marked progress in its crystal quality and accelerated research toward practical devices.[9,31-34) Schottky-barrier diodes (SBDs) and metal-oxide-semiconductor field-effect transistors (MOSFETs) have already been the commercial stage,[35) demonstrating marked reduction in power consumption in railway and appliance applications.

Wide bandgap of GaN has also attracted focused attention as being applied to power devices. Two-dimensional electron gas formed at c-plane AlGaN/GaN heterointerfaces by stress-induced polarization contributes as high electron mobility transistors (HEMTs) or heterojinction field-effect transistors (HFETs).[35-38) Their application targets are extending from high-frequency communication[39,40) to electric power systems. As a power device material, diamond is also highly expected to achieve ultimate performance on the basis of its wider bandgap and higher thermal conductivity than those of the above materials.[41-44)

Research on ZnO was accelerated in the 2000s[3,45] and this material has been expected to be applied to UV LEDs owing to its high exciton binding energy of 60 meV.[46] However, ZnO is not yet competitive because of the difficulty in forming reliable pn junctions and the marked progress of GaN-based LEDs. On the other hand, the research on ZnO has proven that oxides, which had not been considered for use as semiconductors before 1995, can be applied to semiconductor devices when prepared by appropriate techniques such as molecular beam epitaxy (MBE),[47–49] triggering the subsequent advancement of research on various oxide semiconductor devices. Ga_2O_3 is one of examples and is being examined for application to deep-UV detectors[50,51] and power devices[7,52] because its breakdown electric field is estimated to be higher than those of SiC and GaN.

1.3 Purpose of this review

Currently, SiC- and GaN-based power devices are in the spotlight for their potential practical application and social impact. Nevertheless, they have not yet become as widespread as the white LEDs used for lighting.[28] It has often been heard that SiC- and GaN-based power devices are less advantageous over Si-based devices than expected owing to their high cost. Is this true?

A concern is that the characteristics of some SiC- and GaN-based power devices may change during operation owing to undefined physical phenomena and stress. The failure of power devices leads to a dangerous failure of the entire system wherein the power is uncontrollable. For devices that require high reliability, unknown or unexpected phenomena are fatal problems. To achieve the full bloom of SiC- and GaN-based power devices, it is necessary to clarify the physical processes in defects, the causes of deep energy levels, the factors affecting the carrier lifetime, and other basic physical properties of the materials. In-depth clarification of these fundamental properties is a task common with other wide-bandgap semiconductors, such as oxides and diamond, and will contribute to the realization of various applications highlighted by the characteristics of each material.

In this review, the current status of research on wide-bandgap semiconductors toward devices is summarized and the future direction of basic research required for their cutting-edge applications is discussed in order for their "full bloom" to solve the energy crisis which we should not be handed over to our descendants. Note that the focus of this article is only single-crystal materials rather than amorphous or polycrystalline composite oxides such as InGaZnO.

2. Future tasks for GaN-based optical devices

2.1 Current status of GaN-based optical devices

Although GaN-based LEDs became widespread in market shortly after their emergence, their emission efficiency greatly depends on the emission peak wavelength. Figure 2 shows emission efficiencies (external quantum efficiencies) of LEDs with different wavelengths.[53] The efficiency decreases at wavelengths of 500–600 nm (known as the "green gap") and suddenly decreases at wavelengths shorter than that corresponding to the bandgap of GaN (known as the "UV threshold"). Addressing these problems in order to realize LEDs with an efficiency of nearly 100% over a wide wavelength range is the ultimate goal for researchers of GaN-based LEDs.

2.2 Task 1: Emission dynamics

When the first blue LED was realized, researchers wondered why high-brightness emission was achieved despite the presence of dislocations with a density of ~10^9 cm^{-2} in the epilayer. This was later attributed to the emission of excitons localized at deep potential regions, rather than the nonradiative recombination of carriers in defects, as a result of composition fluctuation in the InGaN emission layer.[54] Thus, the emission mechanism of GaN-based LEDs includes physical phenomena different from those in traditional III-V compound semiconductors. The clarification of these phenomena has significantly contributed to the improved emission efficiency and reliability.

For InGaN-based LEDs, the emission efficiency decreases with increasing current density, which is known as the efficiency droop.[55,56] This hampers high-brightness emission, and therefore research to clarify its causes has eagerly been carried out. In particular, a model in which Auger recombination is assumed to be the main cause of nonradiative recombination at high current densities has attracted attention.[57–59] However, Kawakami[60] and Amano[61] pointed out the drawbacks of this model on the basis of their deep investigation on the emission dynamics. Moreover, the efficiency droop is less in LEDs with a reduced number of defects fabricated on GaN substrates,[62] suggesting any physics and mechanisms different from simple Auger recombination associating the efficiency droop.

Kaneta *et al.*[63-65] clarified the correlation between the effect of exciton localization and defects in an ultrasmall region using a scanning near-field optical microscope (SNOM). Compared to cathodoluminescence (CL) technique, special resolution of investigation can be markedly narrowed by using a SNOM, as shown in the top figure of Fig. 3,[63] typically <100 nm. They showed that (i) in the violet-emitting quantum well (QW), shallow localized states enhance carrier diffusion and photoluminescence (PL) intensity mapping is well correlated with threading dislocation (TD) distribution [Fig. 3(a)], (ii) In the blue-emitting QW, deep localized states confine carriers and avoid non-radiative recombination in TDs [Fig. 3(b)], and (iii) in the green-emitting QW, TDs are formed in localized states and cause enhanced trapping of carriers, markedly reducing internal quantum efficiency [Fig. 3(c)]. Later they developed a dual-probe SNOM,[64] and visualized the more detailed processes of carrier motion in space.[65] Photodynamics research on such ultrasmall regions will greatly contribute to improving the efficiency of LEDs and LDs in the future.

2.3 Task 2: Short-wavelength LEDs

LEDs with a wavelength shorter than the UV threshold have an AlGaN active layer and require a wider-bandgap cladding layer. In this case, there are three problems: (1) the threading dislocation density in the AlGaN active layer is high, (2) the fabrication of p-type AlGaN layers is difficult, and (3) the light extraction efficiency is low because of light absorption by the p-contact layer and electrodes.[66] To address problem (1), efforts has been concentrated on reducing the threading dislocation density of AlN buffer layers on sapphire substrates.[67,68] Problem (2) is difficult to address because of the high activation energy of Mg as an acceptor (630 meV[69] in AlN). The formation of a barrier layer against electrons has been attempted to assist the effective transfer of holes into the emission layer.[70] No decisive solution to problem (3) has yet been found, and the light extraction efficiency is only approximately 8% for deep-UV LEDs.[66] In addition, there has been an attempt to utilize the effect of In localization, as observed in InGaN,[54] by doping In into an active layer to form an InAlGaN layer.[71] Owing to these attempts, the efficiency of deep-UV to UV LEDs has been improved, as shown in Fig. 4,[66] but has not yet reached the level of blue LEDs. Further basic research is needed to clarify the emission dynamics in the InAlGaN emission layer and develop some technologies of forming contacts to p-type layers.

Currently, the development of AlN substrates is being accelerated because problem (1) can be solved using AlN substrates.[72,73] Advantages of using AlN substrates have been proved by the growth of high-quality AlN epilayers on AlN substrates[74] and photoexcited laser oscillation using AlGaN/AlN quantum wells.[75] Further progress of AlN substrates is expected in the future.

Meanwhile, there has been an attempt to realize deep-UV emission from AlGaN/AlN quantum wells pumped by an electron beam without forming pn junctions. A power efficiency of 40% and a device output of 100 mW have been achieved for a wavelength of 240 nm.[76]

2.4 Task 3: GaN substrates

To obtain ultrahigh-brightness white LEDs, a high current density is required to drive the LEDs, and hence, the series resistance of the LEDs must be sufficiently reduced. Vertical LEDs using conductive substrates are preferred for this purpose, and GaN substrates are ideal. Although GaN substrates have been used for LDs, large GaN substrates have not yet been fabricated and the fabrication cost of GaN substrates is high. However, the development of GaN substrates has been accelerated in response to the recent progress of GaN-based power devices[45], and a high-brightness LED with a luminous efficacy of 200 lm/W has been achieved.[77] The current status and tasks for GaN substrates, including their application to power devices, will be described later.

2.5 Other tasks

Lighting applications will be a future major goal for GaN-based optical devices. In this case, the improvement of their color-rendering properties is essential and the devices are expected to be studied as a system integrated with appropriate phosphors and LEDs with different wavelengths. Recently, Philips reported the successful development of a lamp with a luminous efficacy of 200 lm/W and high color-rendering properties that can replace fluorescent lamps.[78]

3. Future tasks for SiC-based power devices

3.1 Current status of SiC-based power devices

SiC-based power devices have been making remarkable progress in response to the commercialization of epitaxial growth systems and the reduction in the cost of large SiC substrates with low defect densities. SiC-based SBDs are already in the phase of mass production and 1700 V/75 A devices are in the research and development phase.[79] MOSFETs now have improved control of the interface between the gate insulating film and the SiC substrate[80] and are in the practical phase.[81)]

On the other hand, pin diodes, which are one of bipolar devices, have the advantage that the on-resistance can be reduced by injecting carriers into the i-layer and therefore they are attractive as practical devices with an ultrahigh breakdown voltage. Kimoto and co-workers realized pin diodes with a breakdown voltage of 21.7 kV by reducing the deep levels in SiC and adopting a structure that suppressed the electric-field concentration within the device.[82,83)] The suppression of defects is also a high-priority task for the progress of bipolar junction transistors (BJTs).[84,85)]

The validity of SiC-based power devices has been demonstrated for use in modules for controlling the power of indoor air conditioners[86)] and inverter systems for railway cars.[87)] Power semiconductor modules have also already been commercialized.[88)] Full-power modules using SiC MOSFETs are in the phase of mass production.[89)]

3.2 Task 1: Defects in substrates and epilayers

Since power devices have a large area to carry a large current, the defect density greatly affects the yield and the defects are considered to be device killers. Denoting the defect density as D (cm^{-2}) and the device area as A (cm^2), the yield of a device is expressed by $Y = \exp(-DA)$, as shown in Fig. 5.[90)] For ~10-A-class devices, a defect density of ≤10 cm^{-2} is required to achieve a yield of 80%. However, future 100-A-class devices will require a defect density of ≤0.1 cm^{-2}.

Table II summarizes the type and density of defects in currently available SiC and their effect on decreasing the breakdown voltage.[90)] Micropipes greatly affect device performance but have recently been eliminated to a negligible level. In contrast, threading spiral dislocations (TSDs), threading edge dislocations (TEDs), and basal plane dislocations (BPDs) still remain at high densities, although their effects on the breakdown voltage are not fatal. Figure 6 schematically shows defects in a SiC substrate and how they propagate to the epilayer. Almost all of TSDs and TEDs propagate from the substrate to the epilayer. The majority of BPDs do not propagate to the epilayer but approximately 10% do.[91,92] BPDs that have propagated to the epilayer expand upon the application of forward current in bipolar devices while forming stacking faults, causing the serious problem of deterioration of the forward characteristics of the devices.[93] Hence, the propagation of BPDs from the substrate to the epilayer should be avoided.[94–96] There are still many unclear points in the behavior and control of the above defects, and they are important issues to be addressed in order to improve device performance in the future. For details, readers are referred to Ref. 97.

3.3 Task 2: Insulator/SiC interfaces

The characteristic of insulator/semiconductor interfaces is key in the realization of SiC MOSFETs. When SiC substrates are used, a SiO_2 layer is easily formed by thermal oxidation; however, the interface state density was incredibly high for SiC-based devices introduced in ~2000 and the channel mobility was two orders of magnitude lower than the bulk mobility.[98–102] To overcome this problem, researchers changed the plane orientation[103–105] and the conditions for fabricating oxide layers,[106–108] achieving a channel mobility exceeding 100 cm^2/Vs. Meanwhile, the fluctuation in threshold voltage (V_{TH}) is another problem,[109-116] which may somewhat be associated with issues on channel mobility. Figure 7 shows the capacitance-voltage hysteresis reported by Okamoto *et al.*[117] for a 4H-SiC C-face MOS capacitor processed by wet oxidation. The variation in hysteresis suggests existence of various types of traps, for which we should overcome in order to realize an excellent MOS structure. H_2 postoxidation annealing (POA)[117] and phosphosilicate glass (PSG)/SiO_2 double structure[118] are examples effective to realize simultaneously high channel mobility and low threshold voltage instability. Moreover, it was shown that the use of AlON as a gate insulator increased the breakdown voltage and reduced the leakage current.[83] Although SiC MOSFETs have reached the practical phase,[89] the interface still has a large effect on device performance, and it is an essential task to clarify the physical phenomena at the interface.[119)]

3.4 Task 3: Carrier lifetime and deep levels

Future SiC bipolar devices (*e.g.*, pin diodes, BJTs) are expected to have high voltage and current capabilities. Carrier lifetime is a key physical parameter for these devices because the behavior of minority carriers determines the device performance. For bipolar devices with a breakdown voltage of 20 kV, the necessary carrier lifetime is estimated to be ≥15 μs.[120)] However, an excessively long lifetime worsens the switching performance. Hence, devices should be designed to have an appropriate carrier lifetime in accordance with their purposes.

In ~2000, the carrier lifetime of SiC was only ≤1 μs, even though it was an indirect transition semiconductor.[121)] This value is too small and was attributed to the presence of lifetime-killing defects, that is, carrier recombination centers. Among the point defects in SiC, the $Z_{1/2}$ centers at $E_c - 0.65$ eV are known to act as effective lifetime killers.[122–124)] With the reduction of the concentration of $Z_{1/2}$ centers by optimization of the growth conditions,[125)] carbon implantation and annealing,[126)] and thermal oxidation,[127)] a longer lifetime of 20–30 μs has recently been achieved.[128,129)] A report also showed that a lifetime appropriate for the device can be achieved by controlling the concentration of $Z_{1/2}$ centers through electron beam irradiation and thermal treatment.[124)]

Many of the above studies concern n-type SiC. Although the improvement[130)] and control[131)] of the carrier lifetime in p-type SiC were reported by Hayashi and co-workers, the mechanism of lifetime killers is complicated and the effect of deep levels on the carrier lifetime remains unclear. Thus, controlling the carrier lifetime is essential for achieving future improvements in bipolar devices. It is necessary to clarify the physical factors limiting the carrier lifetime and develop processing techniques on the basis of these factors.

3.5 Other tasks

Many of the physical parameters of SiC have remained unclear and information needed to accurately simulate SiC-based devices is not available. Moreover, there are many issues concerning the fabrication processes for SiC-based devices. For example, high-temperature ion implantation and thermal treatment are required to locally control the conductivity, but these processes may cause defects. The development of new processes is also required in addition to the clarification of these issues. Technology of forming good ohmic electrodes should also be improved.[132)]

4. Future tasks for GaN-based power devices

4.1 Current status of GaN-based power devices

Currently, GaN-based power devices are mainly fabricated by growing heteroepitaxial layers on Si substrates because large GaN substrates have been under the development stage. Attempts have been made to fabricate GaN devices on SiC substrates, but the use of Si substrates is far advantageous in terms of cost reduction for large substrates. However, many defects are likely to thread through the GaN layers and to cause excessive leakage. This may deteriorate performance of devices that carry current in the vertical direction. Therefore, attentions are focused on lateral-structure devices such as HEMTs and HFETs, which use the lateral conduction of a two-dimensional electron gas that is induced by the polarization of AlGaN/GaN heterointerfaces. With this device configuration, GaN has been practically applied to high-frequency power devices for rapid operation before being applied to power devices with high-voltage and -current capabilities.[133-135)]

GaN-based devices are basically normally-on because the formation of a two-dimensional electron gas is caused by spontaneous polarization. For use as power devices, however, they must be normally-off (not conduct current in the normal state) and also have high current capability and low on-resistance.[136,137)]

Recently, GaN-based devices with a breakdown voltage of 600 V have been reported,[138,139)] and the validity of power conditioners equipped with GaN-based devices has also been demonstrated.[140)] In addition, vertical pn-junction diodes and with a breakdown voltage of ≥3 kV using a GaN substrate have been reported.[141)]

4.2 Task 1: Reliability

GaN-based power devices have the problem of unstable performance, which decreases their reliability. The greatest concern is current collapse, in which the drain current decreases owing to the gate voltage stress.[142–145)] Such instability is considered to be due to the combination and release of carriers via traps. Researchers have attempted to address this problem by reducing surface levels through surface passivation[146)] or by thickening the epilayer and inserting a field plate (FP) to suppress the electric field between the gate and the drain,[147–149)] as shown in Fig. 8.[147)] Ohno pointed out that the general Shockley-Read-Hall (SRH) model is unable to explain the causes of current collapse.[150)] The physical mechanism of current collapse has not yet been sufficiently clarified, and further research is needed to elucidate its mechanism and develop control techniques in the future.

It has been pointed out that GaN-based power devices have many other problems related to their reliability, such as unstable on-resistance and leakage current.[151,152)] Many stacking faults are present in the GaN layers on Si substrates and are likely to contribute to unstable device performance. Various basic studies are needed for GaN-based power devices to fully bloom.

4.3 Task 2: Normally-off devices

Various attempts have been made to achieve normally-off GaN FETs.[136,137] Figure 9 (a)-(e)[153] schematically shows the achievements. In these attempts, however, new traps were generated, causing a shift in V_{TH}.[137] Although new structures will be proposed in the future, researchers should be careful to recognize demerits that may underlie apparent advantages. Recently, MOS-HFET[39] and gate injection transistor (GIT)[40] are recognized to be two of the most promising structures, which are illustrated in Fig. 10(a) and (b), respectively.

4.4 Task 3: GaN substrates

Marked efforts and progress have been carried out for GaN substrates.[154] A practical method of growing GaN substrates is hydride vapor phase epitaxy (HVPE).[155–158] As liquid-phase growth methods, the high-temperature high-pressure method,[159,160] the ammonothermal method,[161–163] and the Na flux method[164–167] have been studied for GaN substrates. The dislocation densities have been reported to be 5×10^{7} cm^{-2} for the HVPE method[158] and 10^{3}–10^{5} cm^{-2} for the Na flux method,[165–167] meaning that epilayers with a dislocation density lower than that in GaN/Si (approximately 10^{8}–10^{9} cm^{-2}) can be obtained. The fabrication cost is a concern but the effect of dislocations remaining in the substrates must also be considered. The dislocation density of GaN substrates is not yet competitive with that of SiC substrates, and findings on the behavior of dislocations are limited because of the small number of experiments on homoepitaxial growth. GaN substrates should be further studied to improve their quality and clarify the mechanism underlying the propagation of dislocations during epitaxial growth and their effect on devices.

4.5 Other tasks

Similarly to SiC, GaN still has many unclear physical parameters, such as the breakdown electric field. Device simulation is indispensable for designing device structures and FPs to avoid the effect of current collapse. Research on such physical parameters should be promoted.

5. Future trends of diamond-based and gallium-oxide-based devices

5.1 Current status and tasks for diamond-based devices

Diamond has the potential to realize power devices with the ultimate performance of fast operation at high temperatures with low loss and a high breakdown voltage.[41] Previously, many studies were in the stage of material exploration. However, the rapid low-loss switching performance of SBDs[168] and junction FETs (JFETs) with a low leakage current[169] have recently been reported, indicating the possibility of applying diamond to small semiconductor power devices.

However, there are still many unknown issues concerning the device application of diamond, which has basic problems such as the difficulty of n-type doping, deep donor levels, and a low activation rate. Although P[170–172] and As[173] doping have been attempted to obtain n-type diamond layers, more research on the physical properties of diamond is needed in the future. Interestingly, diamond exhibits superconductivity upon B doping.[174] Anyhow, diamond is highly attractive to materials researchers and may lead to unprecedented novel devices.

A major hurdle in the practical application of diamond devices is the substrate, which is discussed in detail in Ref. 41. As shown in Table III, diamond substrates have many defects and their behavior, propagation to epilayers, and effects on electrical characteristics and reliability remain unclear. These issues must be addressed in future studies.

5.2 Current status and tasks for Ga_2O_3-based devices

Ga_2O_3 has recently attracted attention as a fourth-generation semiconductor material that can be used for power devices. As shown in Table I, Ga_2O_3 has a bandgap wider than those of SiC and GaN. Hence, Ga_2O_3 is expected to have a high breakdown electric field and a low on-resistance R_{on}, which may be estimated by the well-known formula of $R_{on} = 4\ V_B^2 / \varepsilon\mu_n E_B^3$, where V_B, ε, μ_n, and E_B denote the breakdown voltage, the permittivity, the electron mobility, and the breakdown electric field, respectively. Moreover, Ga_2O_3 substrates can be fabricated by a solution method similar to that used to grow sapphire substrates.[175–179]

Sasaki *et al*. fabricated Ga_2O_3 homoepitaxial layers by MBE using ozone as an oxygen source and controlled n-type conduction to within the range of 10^{16}–10^{19} cm^{-3} by Sn doping to obtain a prototype Pt SBD.[52] Higashiwaki *et al*. fabricated MESFETs[7] and then MOSFETs operating even at a high temperature of 250°C,[180] revealing the advantages of Ga_2O_3 for use in electron devices.

The author has engaged in research on Ga_2O_3 and sincerely wishes that this material is fully applied to power devices. It is too early to discuss the superiority of Ga_2O_3 over SiC and GaN, but it is an apparent advantage of Ga_2O_3 that coherent heterostructures are formed[181] and its conductivity can be controlled by ion implantation[182] and thermal treatment.[183,184] However, the issues concerning Ga_2O_3 are wide-ranging and include substrates, crystal growth, control of material properties, device processes, and implementation techniques for improving thermal conductivity. The establishment of a strong collaborative research system supported by the government will greatly accelerate the development of original Ga_2O_3-related technologies.

Currently, the p-type doping of Ga_2O_3 is not firmly established, and this issue must eventually be addressed in the future. The replacement of Ga with Mg or Zn (known as cation replacement common to GaN) may be possible rather than anion replacement in ZnO (doping N), and actually high-resistivity substrates have been shown by Mg doping.[7] Therefore, the advancement of these doping techniques is desired. If p-type Ga_2O_3 is obtained, not only vertical power devices but also deep UV LEDs[185] will be advanced.

There has also been an attempt to use Ga_2O_3 substrates for GaN-based LEDs on the basis of the fact that the substrates have a low resistance and wide bandgap.[186–188]

6. Wide-bandgap oxide semiconductors

As 2-inch ZnO substrates have become commercially available, ZnO is expected to be applied to UV LEDs but research has not yet reached the practical level. Future high-priority tasks concerning ZnO include the formation of stable pn junctions and other basic materials research.[46] In the field of crystal growth, advanced control of the MgZnO composition and MgZnO/ZnO interfaces has been achieved,[189,190] leading to the creation of new spin-related properties.[191,192]

In addition to ZnO and Ga_2O_3, other wide-bandgap oxide semiconductors, for example, SnO_2,[193–195] NiO,[196] Cu_2O,[197] corundum Ga_2O_3 (α-Ga_2O_3),[198] and α-In_2O_3,[199] have attracted attention in terms of functions, and research toward realizing their future device applications is ongoing. Moreover, some researchers have attempted to form alloy crystals of semiconductors and transition-metal oxides with different functions to derive new functions.[200,201] Oxides have various functions and are expected to be applied to devices by adopting new principles revealed by the progress of in-depth research on their properties.

7. Is a substrate a key issue?*

In the evolution of III–V alloy semiconductors, such as AlGaInP and InGaAsP, the development of substrates preceded the growth of crystals, and there was the well-established theory that even a slight lattice mismatch between the substrate and the epilayer greatly affects the crystal quality.[202] In contrast, for wide-bandgap semiconductors, researchers were interested in the properties of materials and tackled the development of small substrates and the exploration of material

* In Japanese, the same word of "kiban" is used both for "substrate" and "key issue" though their Chinese characters are different. In an original publication in Japanese, the author intended to claim that "substrate (kiban)" and "key issue (kiban)" are the equivalent words.

properties of heteroepitaxial layers in parallel. Research on SiC aiming at device applications was carried out using Si substrates before the development of SiC substrates.[203,204] Although ZnSe layers were heteroepitaxially grown on GaAs substrates, strict lattice matching was required between the substrates and the epilayers,[205,206] and the development of ZnSe substrates was carried out to meet this requirement.[207] What the history tells us is that researchers have continuously aimed to develop high-quality substrates as the basis of device applications. Although large SiC and GaN substrates have gradually been obtained, defects in these substrates are not negligible and the uniformity of quality is questionable. Epilayers are considered to take over any problems of substrates in some form. Complete understanding and control of the properties of substrates and the behavior of their defects will be a fundamental technology for future device applications for various wide-bandgap semiconductor materials, not just SiC and GaN.

8. Final remarks

In this review, the issues to be addressed in order for wide-bandgap semiconductors to fully bloom are summarized and the importance of basic research facing to the current status of their research and applications is emphasized. Wide-bandgap semiconductors still have the problems of unsatisfactory yield and reliability, whereas power devices have reached the stage of mass production. Such problems are sometimes attributed to production technologies, but production technologies may sometimes be treated as confidential. We should recognize that wide-bandgap semiconductors still have many unclear physical phenomena, which can be elucidated not by simply optimizing production technologies but by careful investigation of basic physics by specialists. I hope that these noteworthy materials will fully bloom through open discussions that take into account their basic properties.

After the publication of the original version of this article in Oyo Buturi in 2013, progress of wide-bandgap semiconductors has been accelerated.[208-210] Commercial applications of

SiC-based power devices have been further expanded to wide area including railway cars[211], where full-SiC inverters can reduce the train operation power by 20-36%, air conditioners, and power conditioners in photovoltaic systems, together with commercialization of power modules of improved efficiency and compact configuration.[212] Achievements of high-quality SiO_2/SiC interface with the interface state density of as low as $<10^{11}$ cm^{-2}eV^{-1} [213] is a good news supporting evolution of MOSFETs, while understanding of the breakdown phenomena has been advanced.[214] Progress of GaN-based power devices is also noteworthy supported by high quality GaN substrates as well as large area GaN/Si structures. A vertical MOSFET with 1.6 kV blocking voltage on a free standing GaN substrate[215] and normally-off lateral MOSFET with 825 V breakdown voltage on an 8-inch Si wafer[216] are typical examples. Diamond vertical SBD realized forward currents and blocking voltages of more than 1A and 300V at 250 °C.[217] Exploration of LED resulted in first demonstration of an InGaN-based red LED emitting 629 nm with the light output power exceeding 1mW at 20 mA,[218] as well as steady development of high-power white LEDs.[219] It was an exciting news that Profs. Isamu Akasaki, Hiroshi Amano, and Shuji Nakamura were awarded the 2014 Nobel Prize in Physics for the development of efficient blue GaN LEDs.[220] For Ga_2O_3, detailed understandings of the growth processes[221,222] and Al_2O_3/Ga_2O_3 interface properties[223] have been progressed. Novel use of wide-bandgap oxides such as α-Fe_2O_3 for solar calls[224] and α-$(GaFe)_2O_3$ for spintronic applications[225] was demonstrated. Together with the development of alloy semiconductors[226], oxide semiconductors may open new application fields not limited to power devices. We can really feel that wide-bandgap semiconductors are firmly directing to their full bloom being supported by the devotion of researchers for physics in there.

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Shizuo Fujita was born in Osaka in 1955. He graduated Kyoto University in 1978 and then completed a master's course at the Graduate School of Engineering, Kyoto University, in 1980. He became a research associate, and then promoted to an associate professor and a professor at Kyoto University in 1990 and 2001, respectively. He experienced a visiting scholar at North Carolina State University, USA, from 1994 to 1995. He has been engaged in research on wide-bandgap semiconductors, such as group II−VI compound semiconductors (*e.g.*, ZnSe), GaN, and ZnO, and currently is studying Ga_2O_3 and other oxide semiconductors. He is a collaborating member of the Science Council of Japan and a fellow of the Japan Society of Applied Physics.

(Figure Legends)

Fig. 1 Relationship between energy bandgap and bond length for various compound semiconductors promising for practical applications.

Fig. 2 Emission efficiency (external quantum efficiency) of LEDs with different wavelengths.[53)]

Fig. 3 (Top) Observation regions of CL microscope and SNOM. (Bottom) Correlation between effect of localized excitons and defects in ultrasmall region.[63)] The QWs were fabricated on GaN templates grown by the epitaxially lateral overgrowth (ELO) technique, and the phenomena in the seed and wing regions are compared in the lateral direction of the figures (a)-(c).

Fig. 4 Improvement of efficiency for deep-UV and UV LEDs.[66)]

Fig. 5 Relationships among device killer density *D* (cm^{-2}), device area *A* (cm^2), and device yield.[90)]

Fig. 6 Various dislocations in 4H-SiC substrate and their propagation to epilayer.

Fig. 7 Capacitance-voltage hysteresis reported for a 4H-SiC C-face MOS capacitor processed by wet oxidation.[117)]

Fig. 8 Technique for suppressing current collapse in GaN-based devices. Insertion of FP and increase in epilayer thickness.[147)]

Fig. 9 Examples of techniques for achieving normally-off GaN-based devices.[153)]

Fig. 10 Schematic structures of GaN-based MOS-HFET and GIT.

Table I Basic physical properties of various wide-bandgap semiconductor single crystals. Values for Si, GaAs, 4H-SiC, GaN, and diamond are after the ref.2. For ZnO and Ga_2O_3, the sources are given by the reference numbers.

Table II Type and density of defects in SiC and their effects on decrease in breakdown voltage.[90)]

Table III Defect densities analyzed in diamond substrates.[41]

	Si	GaAs	4H-SiC	GaN	ZnO	β-Ga_2O_3	Diamond
Bandgap (eV)	1.12	1.4	3.2	3.39	3.4	4.8-4.9	5.6
Band Structure	Indirect transition	Direct transition	Indirect transition	Direct transition	Direct transition	Direct or indirect transition[5,6]	
Electron mobility (cm^2/Vs)	1,450	8,500	950	2,000	300	300 [7]	4,000
Hole mobility (cm^2/Vs)	450	400	115	350			3,800
Breakdown electric field (MV/cm)	0.3	0.4	3	5		8 [7]	10
Thermal conductivity (W/cmK)	1.3	0.54	5	1.3	~ 1 [3]	~ 0.2 [8]	20
Electron saturation velocity (cm/s)	1×10^7	2×10^7	2×10^7	2×10^7	3.0×10^7 [4]		3×10^7
Relative permitivity	11.7	12.9	10	8.9	~ 8 [3]	10	5.7

Table I

Defect	Density	Decrease in breakdown voltage	Notes
Micropipes	0~0.1 cm^{-2}	50~80 %	detrimental, but eliminated
TSDs	500 cm^{-2}	< 3 %	minor impacts on leakage
TEDs	3000 cm^{-2}	< 3 %	minor impacts on leakage
BPDs	10 cm^{-2}	< 3 %	bipolar degradation
Stacking faults	0.01~1 cm^{-1}	20~50 %	mostly detrimental
Carrot faults	< 0.1 cm^{-2}	20~50 %	almost eliminated
Triangle faults	~ 0.1 cm^{-2}	20~50 %	observed on 4^{o} off-axis
Particles	< 0.3 cm^{-2}	30~80 %	technological issues

Table II

Micropipes	None
TEDs	300 - 10000 cm^{-2}
TSDs	Not available
Mixed-type threading dislocations	150 - 5000 cm^{-2}
Others	Not analyzed ~10000 cm^{-2}
Total density of defects	10000 -100000 cm^{-2}

Table III

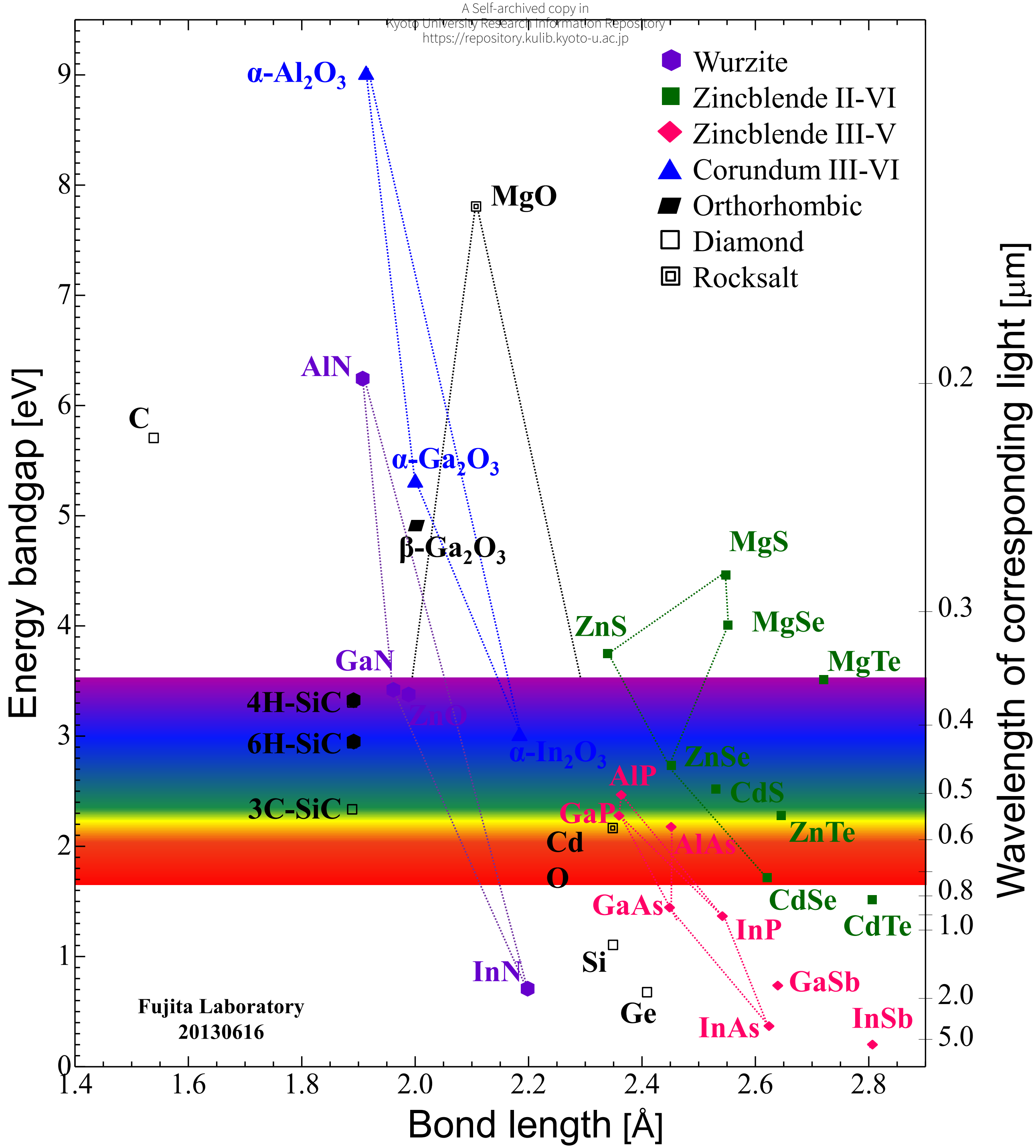

Wurzite
Zincblende II-VI
Zincblende III-V
Corundum III-VI
Orthorhombic
Diamond
Rocksalt
α-Al₂O₃
MgO
AlN
C
α-Ga₂O₃
β-Ga₂O₃
MgS
ZnS
MgSe
MgTe
GaN
4H-SiC
ZnO
6H-SiC
α-In₂O₃
ZnSe
AlP
CdS
3C-SiC
GaP
ZnTe
CdO
AlAs
GaAs
CdSe
InP
CdTe
Si
InN
GaSb
Ge
InAs
InSb
Fujita Laboratory
20130616
Energy bandgap [eV]
Bond length [Å]
Wavelength of corresponding light [μm]
0
1
2
3
4
5
6
7
8
9
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
0.2
0.3
0.4
0.5
0.6
0.8
1.0
2.0
5.0

Fig. 1

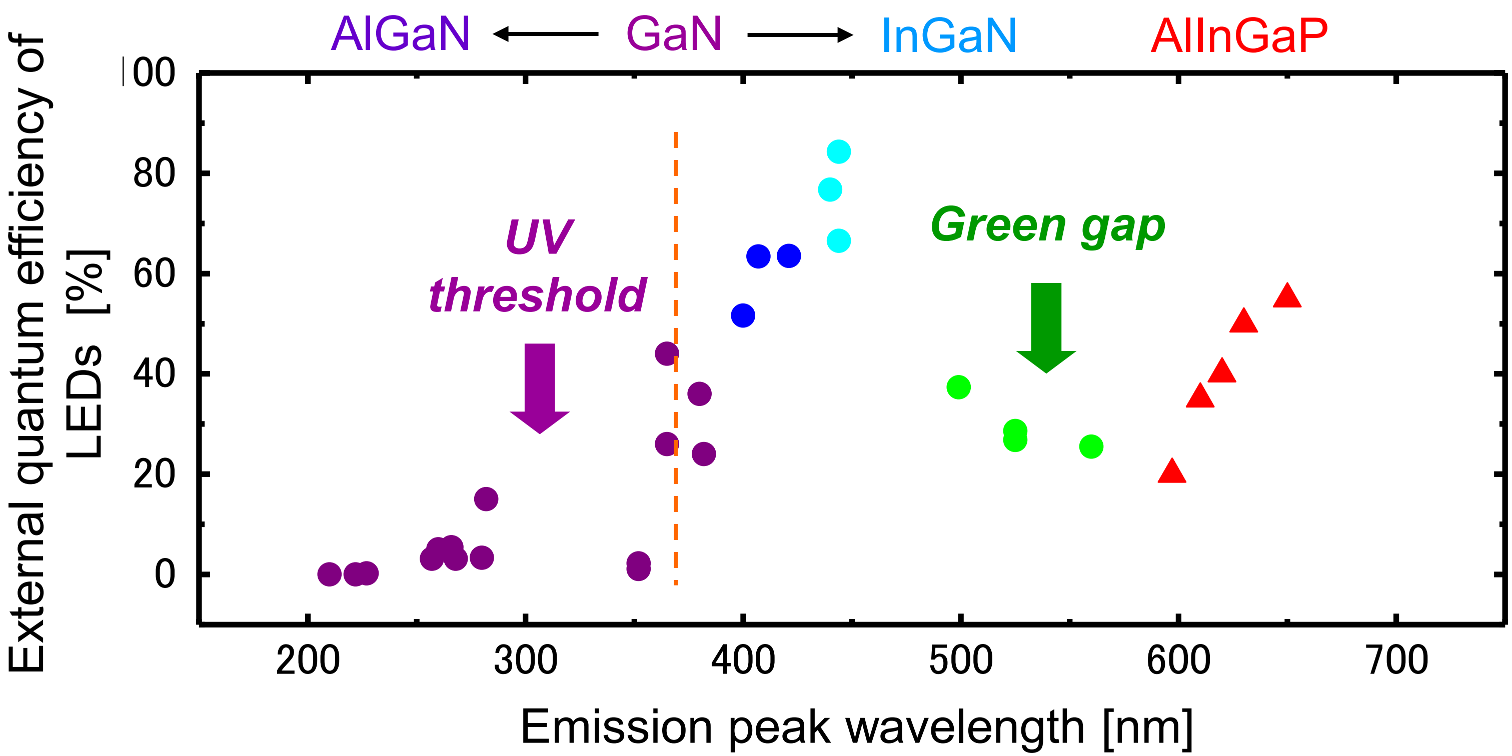

AlGaN
GaN
InGaN
AlInGaP
UV threshold
Green gap
External quantum efficiency of LEDs [%]
Emission peak wavelength [nm]
0
20
40
60
80
100
200
300
400
500
600
700

Fig. 2

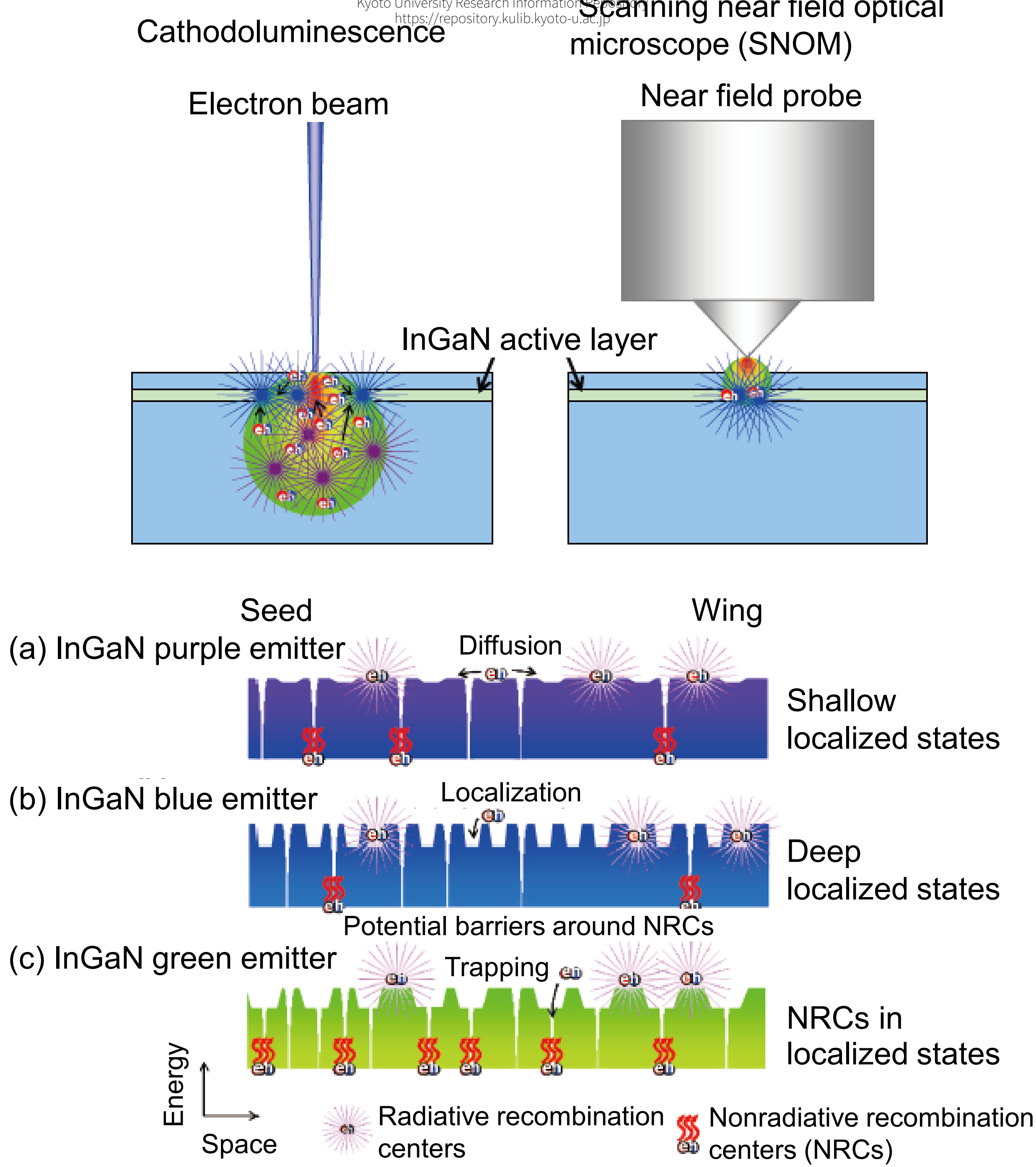

Cathodoluminescence
Scanning near field optical microscope (SNOM)
Electron beam
Near field probe
InGaN active layer
Seed
Wing
(a) InGaN purple emitter
Diffusion
Shallow localized states
(b) InGaN blue emitter
Localization
Deep localized states
Potential barriers around NRCs
(c) InGaN green emitter
Trapping
NRCs in localized states
Energy
Space
Radiative recombination centers
Nonradiative recombination centers (NRCs)

Fig. 3

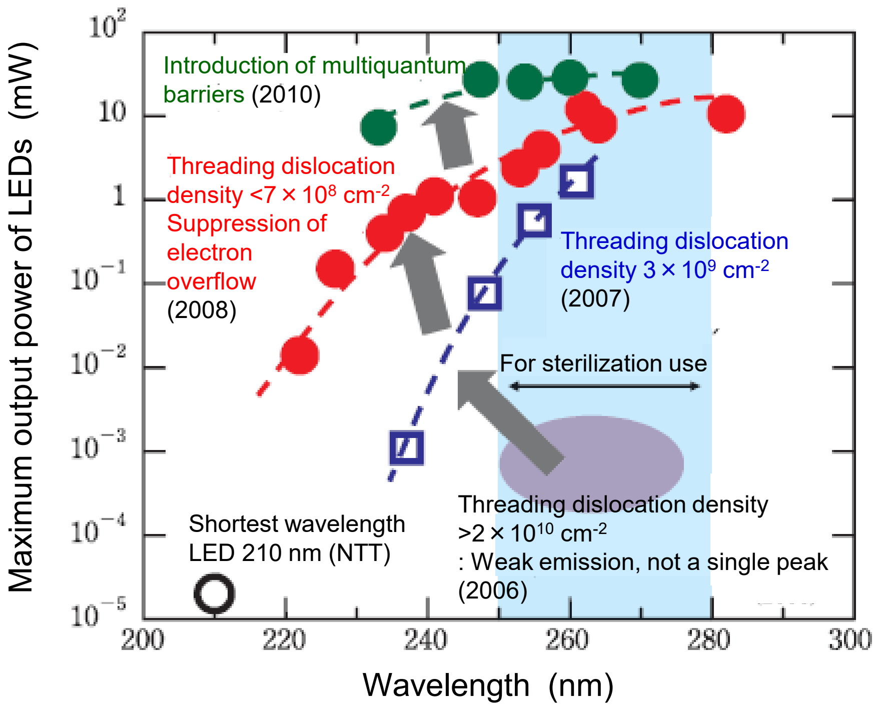

Maximum output power of LEDs (mW)
Wavelength (nm)
Introduction of multiquantum barriers (2010)
Threading dislocation density <7 × 10^8 cm^-2
Suppression of electron overflow (2008)
Threading dislocation density 3 × 10^9 cm^-2 (2007)
For sterilization use
Threading dislocation density >2 × 10^10 cm^-2
: Weak emission, not a single peak (2006)
Shortest wavelength LED 210 nm (NTT)

Fig. 4

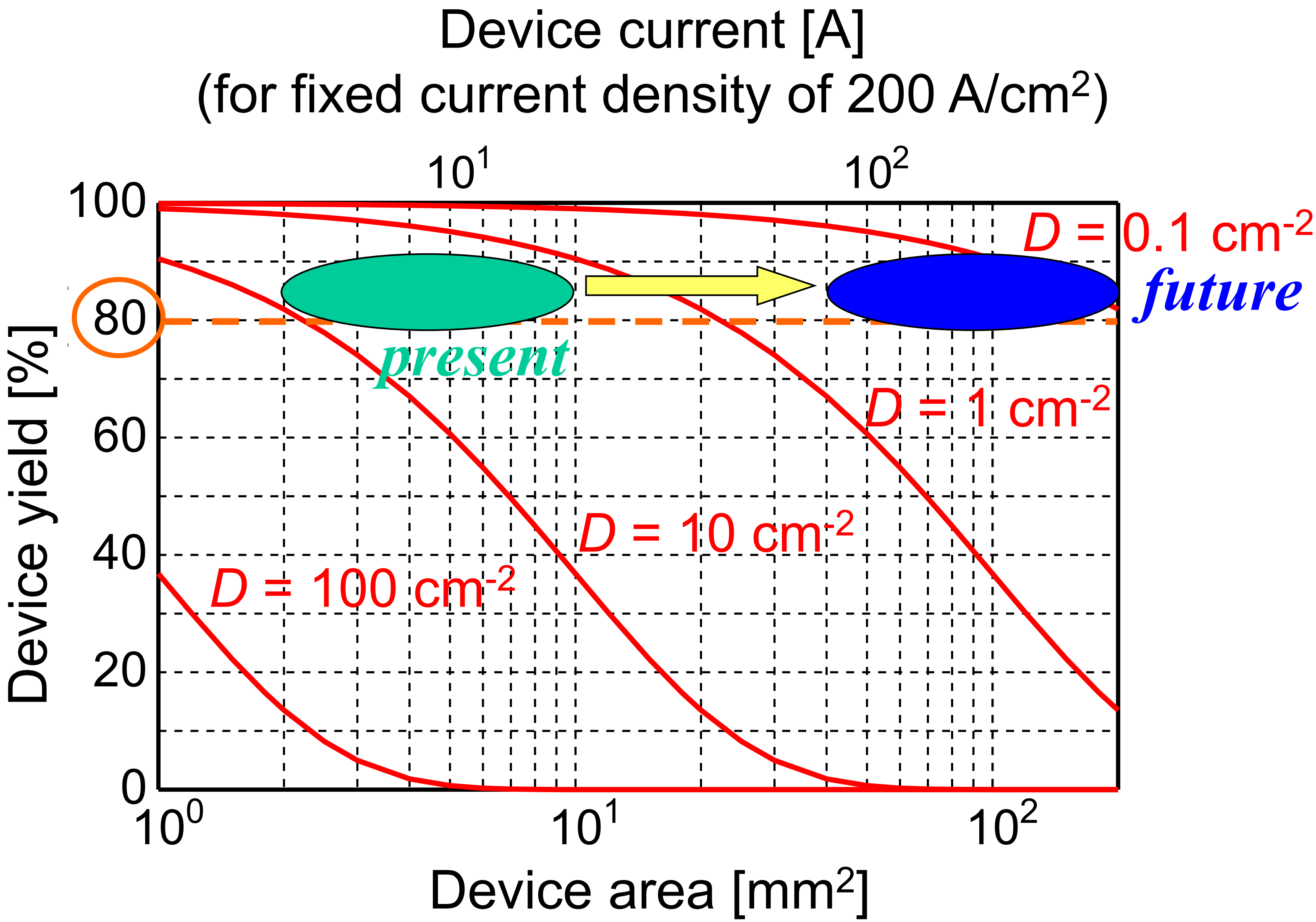

Device current [A]
(for fixed current density of 200 A/cm²)
10¹
10²
100
80
60
40
20
0
10⁰
10¹
10²
Device yield [%]
Device area [mm²]
D = 0.1 cm⁻²
future
present
D = 1 cm⁻²
D = 10 cm⁻²
D = 100 cm⁻²

Fig. 5

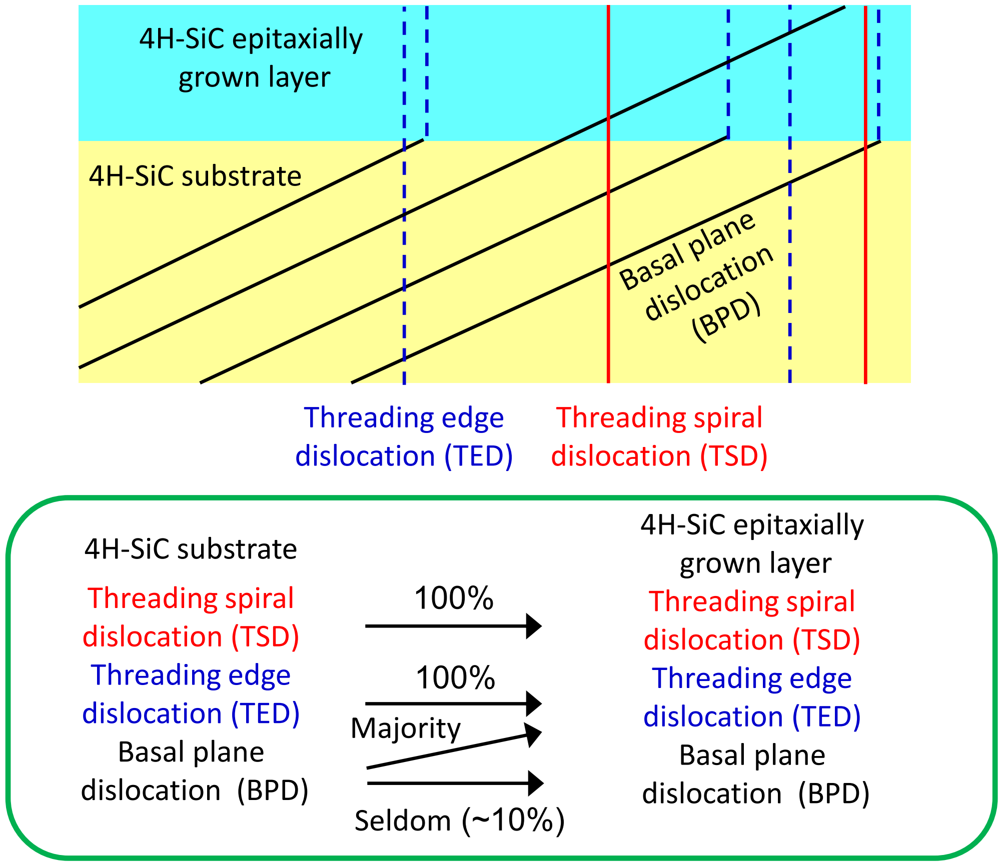

4H-SiC epitaxially grown layer
4H-SiC substrate
Basal plane dislocation (BPD)
Threading edge dislocation (TED)
Threading spiral dislocation (TSD)
4H-SiC substrate
4H-SiC epitaxially grown layer
Threading spiral dislocation (TSD)
100%
Threading spiral dislocation (TSD)
Threading edge dislocation (TED)
100%
Threading edge dislocation (TED)
Basal plane dislocation (BPD)
Majority
Seldom (~10%)
Basal plane dislocation (BPD)

Fig. 6

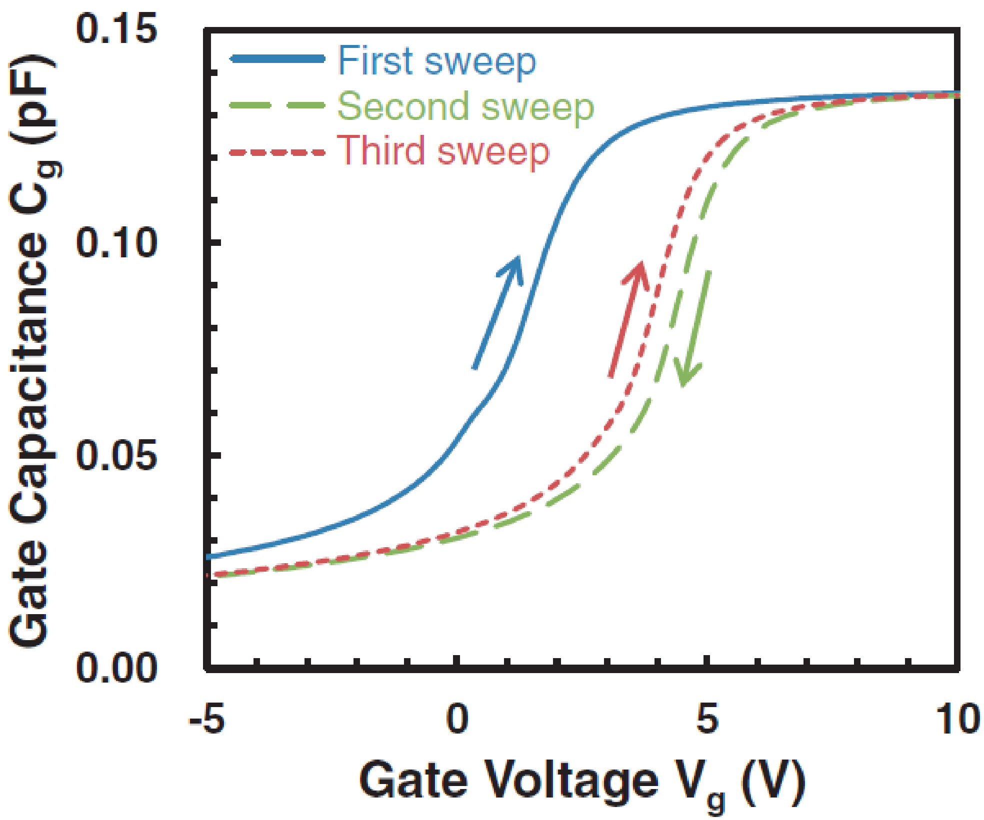

0.15
0.10
0.05
0.00
Gate Capacitance C_g (pF)
First sweep
Second sweep
Third sweep
-5
0
5
10
Gate Voltage V_g (V)

Fig. 7

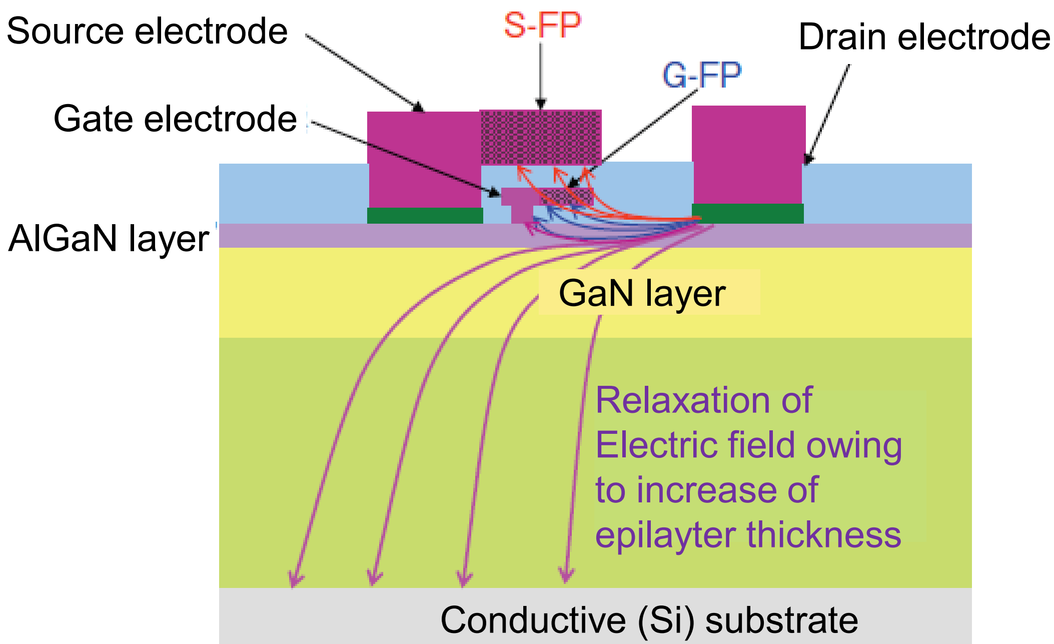

Source electrode
S-FP
Drain electrode
G-FP
Gate electrode
AlGaN layer
GaN layer
Relaxation of
Electric field owing
to increase of
epilayter thickness
Conductive (Si) substrate

Fig. 8

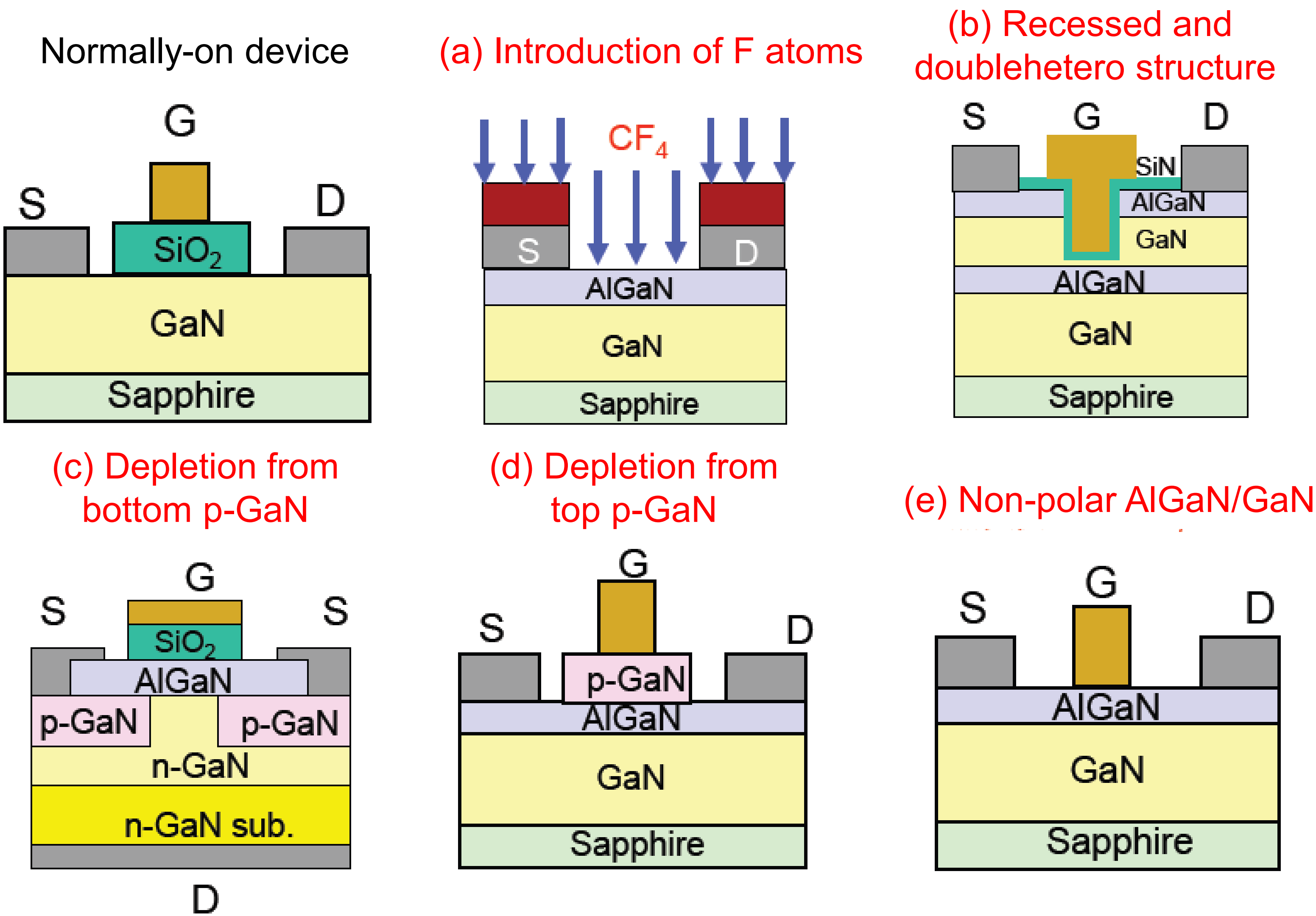
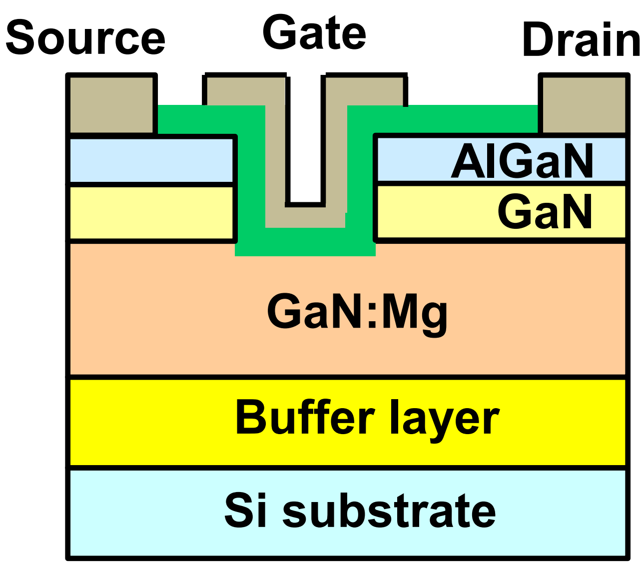
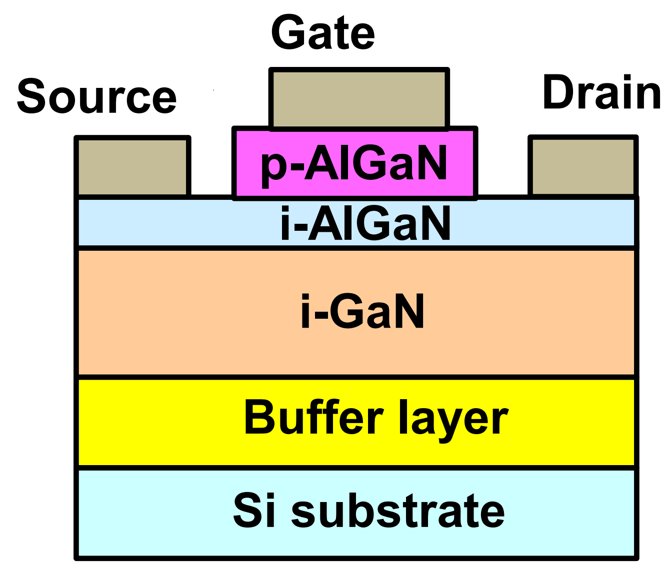

Normally-on device
G
S
D
SiO2
GaN
Sapphire
(a) Introduction of F atoms
CF4
S
D
AlGaN
GaN
Sapphire
(b) Recessed and doublehetero structure
S
G
D
SiN
AlGaN
GaN
AlGaN
GaN
Sapphire
(c) Depletion from bottom p-GaN
G
S
S
SiO2
AlGaN
p-GaN
p-GaN
n-GaN
n-GaN sub.
D
(d) Depletion from top p-GaN
G
S
D
p-GaN
AlGaN
GaN
Sapphire
(e) Non-polar AlGaN/GaN
G
S
D
AlGaN
GaN
Sapphire

Fig. 9



(a) MOS-HFET



(b) GIT

Fig. 10